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AN AERODYNAMIC DESIGN METHOD FOR TRANSONIC AXIAL FLOW COMPRESSOR STAGE

by

Zhu Fang-Yuan, Zhou Xin-Hai, et al

FOREIGN TECHNOLOGY DIVISION

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AN AERODYNAMIC DESIGN METHOD FOR TRANSONIC AXIAL FLOW COMPRESSOR STAGE

Zhu Fang-Yuan, Zhou Xin-Hai, Liu Song-Ling, Fan Fei-Da

I. INTRODUCTION

In the beginning of the 50's, Professor Wu Zhonghua proposed the theory of three-dimensional gas flow in fan blade machines and through iteratively solving the S_1,S_2 stream surfaces to find the 3-D flow field, established the theoretical basis for applying the 3-D flow model to the aerodynamic design of fan blade rotor machines.

Since the latter part of the 60's, a series of reports [2]-[7] published abroad introduced the experimental and computational results of applying 3-D theory in the design of a transonic compressor stage. Multiple-circular-arc (MCA) airfoils are used in these transonic stages. According to the data in these reports, the experimental vlaues and the design values of the average stage properties and of the radial stream parameter distributions may be considered to be in agreement, thus proving that good results may be obtained by applying 3-D theory to the design of transonic stages and that MCA airfoil can be used in transonic stage design.

Based on an analysis and study of the quoted references, we established an aerodynamic design method for a transonic axial flow compressor stage and developed a computer program for it.

Our computational method consists of:

(1) <u>The computation of the average S_2 stream surface--computation of the flow fields at the blade leading and trailing edges</u>

The streamline curvature method is used with the calculation station at the blade leading and trailing edges, the projections of which on the meridional planes may be arbitrary curves. In the calculation, the effects of radial gradients of entropy, enthalpy and

streamline curvature are taken into account. The results of computations are the flow parameters of the average S_2 stream surface at the blade leading and trailing edges.

(2) Approximate calculations of S_1 stream surface of revolution

The practical application of current design is the approximate calculation of an S_1 stream surface with selected blade parameters. The purpose is to check the aerodynamic properties of the selected blades. In our method, the approximate calculation of the S_1 stream surface consists of:

A. Free stream calculation

The free stream calculation is an integral part in the approximate calculation of the flow field of the cascade entrance region of S_1 stream surface. Based on the known position of S_1 stream surface and the leading edge flow parameters, it is the calculation of the parameter distribution along the streamline from the leading edge under the condition that the entropy and $C_o r$ are constant. The result is used as the primary data for checking the incidence angle and the choking margin of the blade channel in the blade parameter calculation. The effects of the variation of streamline radial position and stream surface thickness on flow parameters have been considered in the calculation.

B. Calculation of MCA airfoil parameters

The MCA airfoil parameters are calculated on a plane tangential to the conical surface which is used to approximate the S_1 stream surface of revolution. The centerline angle of attack of the MCA airfoil, the lag angle, the ratio of front chord to total chord, the ratio of front camber to total camber are all determined by requiring suitable values respectively for the incidence angle (the unique incidence angle or the suction surface leading edge incidence angle), the impinging point of the channel shock on the blade suction surface, and cascade channel choke margin. An MCA airfoil may then be

determined with other given conditions. In the calculation, the variations of the airstream relative drag parameter and the variation of stream surface thickness have been taken into account.

(3) <u>Blade shape and blade stacking</u>

Based on MCA airfoil parameters already calculated, we form the airfoil sections on the developed surface of the conic surface. In order to maintain the basic characteristics of plane surface circular arc on a conical surface, we approximate a circular arc with curves of equal turning rate. After forming the airfoil sections along the various stream surfaces at blade height, we stack the various airfoil sections into a blade according to certain requirements and find the airfoil surface coordinates on the various cross-sectional areas. The principle for this part as well as for the computer program is exactly the same as that of [9].

II. CALCULATION OF FLOW FIELD OF THE BLADE LEADING AND TRAILING EDGES

According to the continuity equation, momentum equation, energy equation and state equation of a non-viscous fluid, and from the relationship (see Figure 1),

$$\frac{\partial}{\partial l} = \cos\lambda \frac{\partial}{\partial r} + \sin\lambda \frac{\partial}{\partial z} \quad \frac{\partial}{\partial m} = \sin\varphi \frac{\partial}{\partial r} + \cos\varphi \frac{\partial}{\partial z},$$

we can derive the principal equation of the streamline curvature method at calculation station 1 along the curve to be

$$\begin{aligned} \frac{\partial C_m}{\partial l} = & \frac{gR}{C_m}\left(\frac{K}{K-1}\frac{\partial T^*}{\partial l} - \frac{T^*}{\sigma}\frac{\partial \sigma}{\partial l}\right) - \frac{C_u}{C_m}\frac{\partial (rC_u)}{\partial l} - \frac{C_u^2}{C_m}\frac{K-1}{2K}\frac{1}{\sigma}\frac{\partial \sigma}{\partial l} \\ & - \frac{C_m}{1-M_m^2}\left[\frac{1+M_\theta^2}{r}\sin\varphi\sin(\varphi+\lambda) + \frac{\sin(\varphi+\lambda)}{R_m}\mathrm{tg}(\varphi+\lambda)\right. \\ & \left. + \mathrm{tg}(\varphi+\lambda)\frac{\partial \varphi}{\partial l}\right] - C_m\frac{\cos(\varphi+\lambda)}{R_m} - C_m\frac{K-1}{2K}\frac{1}{\sigma}\frac{\partial \omega}{\partial l}, \end{aligned} \tag{2-1}$$

$$\frac{\partial G_B}{\partial l} = 2\pi g r \rho C_m \cos(\varphi+\lambda), \tag{2-2}$$

where [redacted] . A is the mechanical equivalent of heat.

In the computer program, the "Runge-Kutta" method is used to solve the set of equations (2-1), (2-2) to obtain the meridional velocity C_m along the calculation station and the flow distribution from the calculation point to the root section.

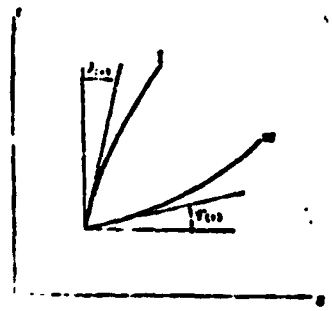

Figure 1

A double-spline function is used to approximate the projection of the flow line in the meridian plane, i.e., equivalent stream points are first approximated by a spline function from which the streamline tangent tg ϕ is found. Then the flow line tangent is again approximated by a spline function from which the flow line curvature is found.

There are two methods to choose in the computer program for estimating the loss in the blade row. One is to determine from the available data the rotor isentropic efficiency and the radial distribution of the stator total pressure recovery coefficient. The other is to calculate the airfoil loss from the relationship between the given dispersion factor and the loss parameter. In the calculation, the stream parameters of the last iteration are used to compute the dispersion factor and the loss coefficient in the current iteration. When the flow field converges, the stream parameters and the loss coefficient will also agree (within allowed error limits).

Tables 1 and 2 show the calculated results in comparison with the data given by [2] and [3].

III. FREE STREAM CALCULATION

The problem to be solved in a free stream calculation is to find the suction surface neutral point connected to the cascade unique incidence angle and to provide original data for calculating the shock loss.

By free stream is meant the stream flow from the leading edge with only the effect of flow construction in the meridian plane without the reaction of the blades. Hence, the free stream should satisfy the following conditions:

(1) the free stream $C_{\theta}r$ value is the same as that of the leading edge stream along the same streamline
(2) isentropic flow
(3) axial symmetric flow.

In the presence of rotor blades, the average circumferential stream parameters in the entrance region between the cascade entrance to the first covering surface of the channel (both the suction surface neutral point and the channel shock are located in this entrance region) may still be approximately regarded as satisfying the three conditions stated above due to the cancellation of the leading edge shock wave and the expansion wave as well as the facts that the stream flow is not much restricted by the blades before entering the cascade channels and that the front section of the MCA airfoil of the ultrasonic incident flow is relatively flat.

Based on the average S_2 stream surface calculation, the free stream calculation is carried out with continuous functions along the streamline according to the above conditions.

The principal formula in this program is:

$$C_m = \frac{1}{2\pi g}\,\frac{1}{r\rho}\,\frac{1}{\cos(\varphi+\lambda)}\,\frac{d\Gamma_0}{dl}, \qquad (3\text{-}1)$$

$$g\rho = \frac{p^*}{RT^*}\left(1 - \frac{K-1}{2}\,\frac{C_m^2+C_\theta^2}{KgRT^*}\right)^{\frac{1}{K-1}}. \qquad (3\text{-}2)$$

[redacted] are calculated. They are used in the calculation of airfoil parameters.

IV. CALCULATION OF MCA AIRFOIL PARAMETERS

The blade formation in our design method is carried out on the conic expansion surface. The calculation of airfoil parameters is to

provide the necessary data for blade formation and stacking.

The major problems involved in the calculation of airfoil parameters are discussed below:

(1) <u>On what plane surface are the airfoil parameters to be calculated?</u>

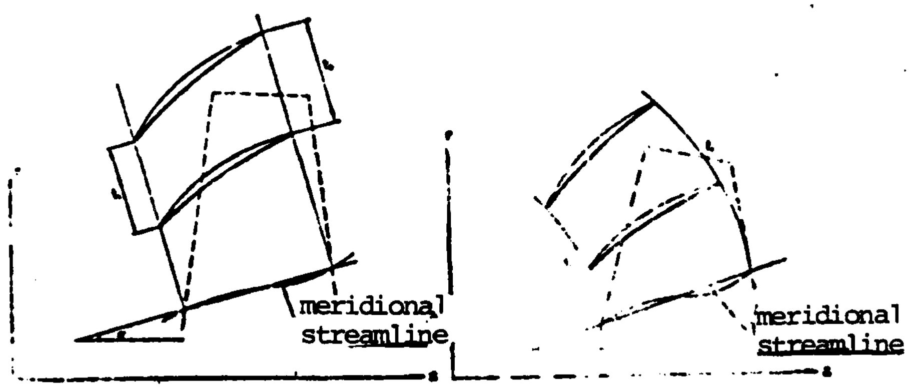

Figure 2

In our opinion, there are two possible ways to do this: one is to use the tangent plane to the conical surface and the other is to use the developed conical surface. In the former, the bowl and suction surfaces of the airfoil are composed of two sections of circular arc, respectively, while in the latter they are composed respectively of two sections of constant turning rate curves (see Figure 2).

According to the unique incidence angle principle, when the relative M number of the incident flow exceeds 1.ϕ, it is necessary in the design to calculate the Mach wave system in the cascade entrance region. When calculated on the tangential plane to the conical surface, this Mach wave system is obtained by using a two-dimensional stream model with three-dimensional stream corrections.

If the airfoil is designed not by following the unique incidence angle principle but by choosing the leading edge suction surface incidence angle, then it is not necessary to calculate the cascade entrance Mach wave system. The second method can also be used.

This has been carried out in [9].

In our computer program the first method is adopted. In addition, while the cascade choking situation is being checked, we also consider the changes in cascade distance along the conical surface, the changes in the airstream relative drag parameter and the changes in the stream surface thickness. Calculation indicates that the various airfoil parameters thus obtained are more reasonable. The calculated results and the data from [3] are both listed in Table 3.

(2) <u>Calculation of lag angle</u>

In principle, lag angle calculations are all based on the Carter formula with corrections to take into account of the effect of three-dimensional flow. In general, there are two methods of treatment: One is to calculate with the airfoil turning angles in [2], [3] and the other is to calculate with the airfoil equivalent turning angle as in [5], [9].

A. Calculation with airfoil turning angle

The computational formulas are

$$\delta = \frac{m\phi}{\sqrt{\sigma}} + X$$

$$= \frac{\beta_{2m} - \beta_{1m} - i}{\sqrt{\frac{c}{m}} - 1} + X \frac{\sqrt{\sigma}_{m}}{\sqrt{\frac{\sigma}{m}} - 1}. \qquad (4.1)$$

where [redacted] is the empirical correction when 3-D flow effect is taken into account.

B. Calculation with airfoil equivalent turning angle

In [10], it is suggested that the velocity triangle at the stream surface cascade entrance be transformed into an equivalent velocity triangle. The condition for transformation is: the exit meridional velocity and radial coordinate are the same as at the entrance, and the $C_{\theta}r$ value is equal to that of the original velocity

triangle at the entrance. Based on these conditions, the equivalent exit stream angle is

$$\beta_{2me} = ctg^{-1}\left\{\left[\frac{u_2}{C_{m2}} - \frac{r_1}{r_2}\left(\frac{u_1}{C_{m2}} - \frac{C_{m1}}{C_{m2}} ctg\,\beta_{1m}\right)\right]\right\}. \tag{4-2}$$

The formula for calculating the lag angle is

$$\delta = \frac{\beta_{2me} - \beta_{1m} - i}{\frac{\sqrt{\sigma}}{m} - 1}. \tag{4-3}$$

In [5], airfoil section formation is carried out on the cascade projection surface and the equivalent exit stream angle is to be located on this plane.

[redacted]

The airfoil equivalent turning angle on the cascade projection surface is used to calculate the lag angle.

In our program, (4-1) is used to calculate the airfoil lag angle.

(3) <u>Calculation of the suction surface neutral point and unique incidence angle</u>

When the airfoil is designed according to the unique incidence angle principle, the suction surface neutral point needs to be located. It is pointed out in [2] that it is a very good approximation to take as the neutral point the mid-point between the airfoil leading edge and the starting point of the Mach wave at the suction surface upper seal. This assumption has been verified by detailed stream diagrams.

The calculation method used in our program is to first obtain the distribution of the stream angle β_m and the relative M number along the streamline through the free stream calculation. Then the Prandtl-Meyer formula is used to calculate the M number as the stream angle of the free stream is turned to be parallel to the direction of the tangent line of the local airfoil suction surface. Then the distribution of the M number along the airfoil suction

surface, and from it the neutral point may be found. For 3-D flow, the tangent line of the neutral point airfoil section should agree with the direction of the local free stream. However, after the choking reaction on the blade and the attached surface on the blade is taken into consideration, it is proposed in [2] that there should be an angle of attack of about +1.5° between the tangent line of the neutral point airfoil section and the local free stream.

The leading edge median angle of attack and the leading edge suction surface angle of attack computed according to the above method are listed in Table 3. The data from [3] are also listed.

(4) <u>Shock position and shock loss</u>

The model of the cascade channel shock is shown in Figure 3. From the A point on the leading edge, draw a normal to the channel median and intersect the suction surface of another blade at B. The normal AB is then a normal shockwave. The methods used to calculate the M number in front of the shock in [2] and [3] are different. We adopt the method in [3], namely that the critical area ratio $\left(\frac{A}{A^*}\right)_1$ in front of the shock is found first from which the M number in front of the shock is then obtained.

From the distribution of the free stream critical area ratio $\left(\frac{A}{A^*}\right)_\infty$, the critical area ratio in front of the shock is

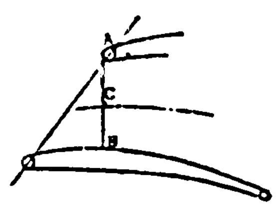

Figure 3

$$\left(\frac{A}{A^*}\right)_1 = \left(\frac{A}{A^*}\right)_\infty \frac{2r_m}{t\sin\beta_\infty} = \left(\frac{A}{A^*}\right)_\infty \frac{r_m}{\pi r\sin\beta_\infty} \tag{4-5}$$

where t, r, β_∞ are respectively the cascade distance, radial coordinate and free stream angle relative to point C and γ_m is the radius of the interior circle tangential to the channel with center at C.

The relationship of $\left(\frac{A}{A^*}\right)_1$ and the Mach number M_1 in front of the shock is

$$\left(\frac{A}{A^*}\right)_\infty = \frac{1}{M_\infty}\left[\left(\frac{2}{K+1}\right)\left(1+\frac{K-1}{2}M_\infty^2\right)\right]^{\frac{K+1}{2(K-1)}}. \qquad (4\text{-}6)$$

In Figure 3, there is a definite requirement on the position of the intersection point between the shock and the suction surface. In [3], it is required that the distance from this point to the leading edge of the blade near the airfoil tip should be about 1.25 b_f. The value will vary at different radii. The parametric chord length ratio b/b_f of the MCA airfoil should be adjusted based on this requirement.

(5) Checking for channel choking

The cascade channel on the tangent plane of the conical surface is shown in Figure 4. Except for the base blade, airfoil bowls are formed according to the cascade distance on the conical surface in a direction opposite to the rotational direction. Cascade channels are formed between the base blade suction surface and the airfoil bowl. Owing to the variation of the cascade distance on the conical surface, the airfoil bowls formed are different from those of the base blade.

The shock loss is calculated with the method mentioned before. The airfoil loss coefficient [illegible] is the difference between the total loss coefficient $\bar{\omega}_r$ obtained from the computation of the blade leading and trailing edge flow fields and the shock loss coefficient $\bar{\omega}_s$.
No loss is assumed in front of the point of intersection between the shock and the suction surface. The airfoil loss coefficient is assumed to be linearly distributed from this point to the trailing edge of the airfoil.

The formula are

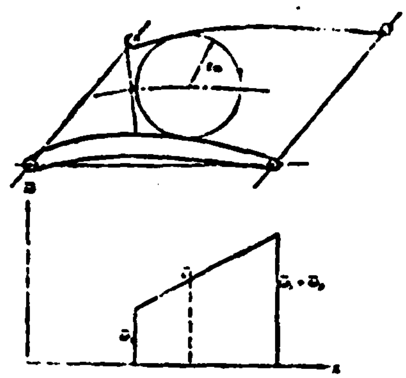

Figure 4

$$\bar{\omega} = \bar{\omega}_1 + \frac{\bar{\omega}_t - \bar{\omega}_1}{b - X_{1a}}(X - X_{1a}), \qquad (4\text{-}11)$$

The minimum value for A/A^* is required to be 1.02-1.05. When this range is exceeded, the airfoil parameter camber ratio F. may be adjusted. Calculation indicates that in the neighborhood of the blade tip, adjusting the camber ratio does not affect much the minimum value of A/A^* while in the neighborhood of blade root, the camber ratio does affect the minimum value of A/A^*.

The results of the calculation are shown in Table 3.

V. CONCLUSIONS

Based on the original given conditions and design requirement, the design method and computer program mentioned in this paper is capable of obtaining the data needed for calculating the blade airfoil section coordinates and strength required in the manufacturing of the blade, through the iteration of the blade leading and trailing edge flow field computation, the approximate computation of the S_1 stream surface of revolution and blade airfoil section formation and stacking.

Sample calculation indicates that the result is good. Hence, an effective tool is provided by the method and computer programs in this paper for current aerodynamic design of transonic axial flow compressor stage.

TABLE OF SYMBOLS

A	mechanical equivalent of heat, area
A/A^*	ratio of area to critical area
a	distance from leading edge to point of maximum camber
b	chord length
c	absolute flow velocity
F_s	camber ratio
G_B	flow rate between calculation point and
g	gravitational acceleration
H	total enthalpy
i	incidence angle
K	index of
l	curvature calculation station
m	meridional streamline, parameter used to calculate the lag angle
M	Mach number
N_n	number of blades
p	pressure
S	entropy of flow
R	gas constant
γ	radial coordinate
T	temperature
t	cascade distance
u	circular velocity
W	relative velocity
X	correction to lag angle
Z	axial coordinate
α	stream surface conical angle
β	relative
γ	airfoil angle
δ	lag angle
ϕ	airfoil
φ	angle between meridional streamline and the Z axis
ρ	gas density
ω	rotor angular velocity
$\bar{\omega}$	total pressure loss coefficient
σ	cascade solidity, function of entropy
λ	angle between calculation station l and γ axis

Angle subscript:

*	choke parameter
f	airfoil front section
F	free flow
γ	radial
S	shock
p	airfoil
sh	shock
m	meridional streamline
Z	axial
θ	circumferential
c	airfoil centerline
ss	suction surface leading edge
C	equivalent velocity triangle
W	relative parameter
L	blade leading edge
B	neutral point
1	blade leading edge flow parameter
2	blade trailing edge flow parameter
C	flow parameter of machine's far upstream

TABLE 1. COMPARISON OF FLOW PARAMETERS AT THE BLADE LEADING AND TRAILING EDGES

FLOW RATE %

STAGE ROTOR	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
STAGE STATOR	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	107.21	100.07	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

NOTE: In this table, 1 denotes calculated values from our program and 2 denotes values given by [3]

TABLE 2. COMPARISON OF FLOW PARAMETERS AT THE BLADE LEADING AND TRAILING EDGES

FLOW RATE %	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
ROTOR	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
STATOR	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

NOTE: In this table, 1 denotes calculated values from our program and 2 denotes values given by [2]

TABLE 3. COMPARISON OF CALCULATED VALUES OF FIRST STAGE ROTOR AIRFOIL PARAMETERS

flow rate

parameter

[illegible]

NOTE: In this table, 1 denotes the calculated values with our program and 2 denotes the values given by [3]

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SUMMARY

An Aerodynamic Design Method for Transonic Axial Flow Compressor Stage

Zhu Fangyuan, Zhou Xinhai, Liu Songling, and Fu Feida

A three dimensional aerodynamic design method for transonic axial flow compressor stage is described in detail in this paper in order to make it easier to apply and more widely used. The method comprises three main parts: the mean S_2 streamsurface calculation, the approximate calculation of S_1 streamsurface of revolution, and defining the blade element on the conical surface and stacking the blade airfoil sections. The method is unusual in that the calculation stations for making the S_2 streamsurface computations are curves, and particularly in that the airfoil parameters of blade are calculated on a plane tangent to the approximate streamsurface of revolution. On this tangential plane, two dimensional flow is used as a basic model to calculate the Mach wave system on the suction surface of cascade entrance region.

The streamline curvature method is used to calculate the flow field on mean S_2 streamsurface. The projections on meridional planes of the blade leading and trailing edges, are selected as calculation stations. Along curved calculation stations, the principal equations, in which the streamline curvature and the gradients of enthalpy and entropy are taken into account, are derived from the fundamental equations of non-viscous axisymmetric flow. The Runge-Kutta method is used to solve the principal equations. The slope and curvature of the streamline are found by means of the spline and double spline functions respectively.

The approximate calculation of S_1 streamsurface of revolution consists of the free stream calculation and the blade airfoil parameters calculation. The free stream in cascade entrance region is calculated for the purpose of performing the calculation of unique incidence angle and the analysis of choking margin of blade channel. In the free stream calculation, the continuity equation is used to obtain the flow parameters, and the basic assumption adopted is that the entropy and $V_\theta r$ are constant on each streamline.

The multiple-circular-arc (MCA) airfoils are used for both the rotor and the stator. The parameters of MCA airfoils are calculated on a plane which

Cont'd

[illegible] maximum [illegible] its [illegible]
[illegible] fulfilling [illegible] these parameters
[illegible] the required values of the
[illegible] angle, and of the distance
[illegible] their impinging point on the

[illegible] the previously obtained MCA
[illegible] plane to the developed conical
[illegible] is approximated by the constant
[illegible] used in this step and used to
[illegible] same as those in reference [illegible]
[illegible] with those
[illegible] Therefore, [illegible]

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